

Thermal deformation study

3/12/2008

Three different ladder support structures have been analyzed for thermal generated mechanical distortions. The stability requirement is that the detector pixels be held within a 20 micron window. A challenge in meeting this requirement is controlling thermal expansion and contraction. The source of the challenge is the large CTE of the aluminum/kapton cable compared to the other components of the assembly. The purpose of this study is to provide rough numbers to compare solutions and gain insight into the problems. More detailed analysis will be required in the future.

ALICE style support

The first structure to be addressed is the ALICE style beam. The geometry shown in Fig. 1 is composed of a thin carbon composite shell supporting 4 detector ladders. The ladders are a sandwich with detector silicon on top followed by adhesive, aluminum/kapton flex PC cable, adhesive and a carbon composite base layer.

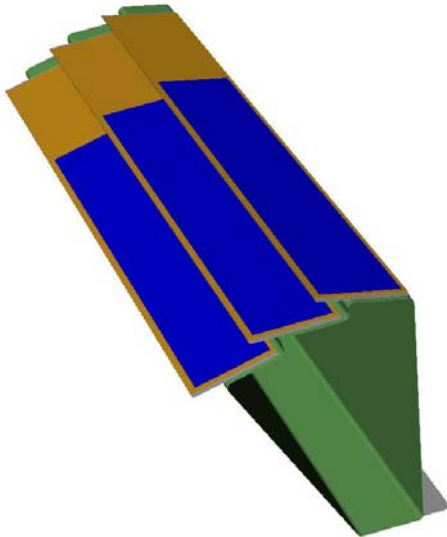


Fig. 1a Sector module made up of a carbon composite support beam with 4 detector ladders

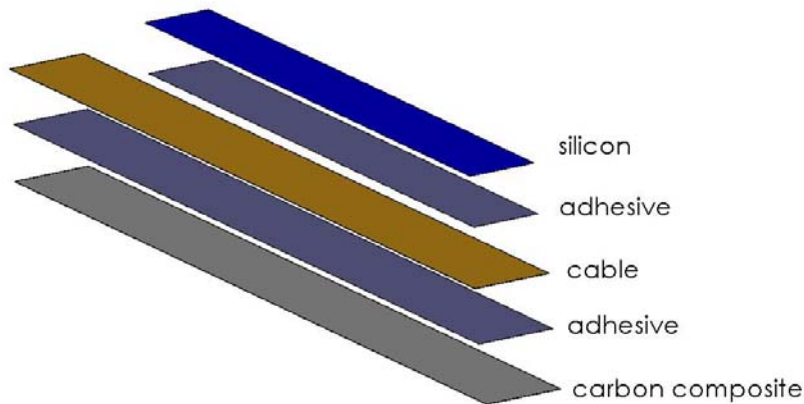


Fig 1b Exploded view of the ladder showing components. The silicon is composed of 10 ~square chips, but it is shown here as a continuous piece of silicon as it has been modeled.

Bimetal thermal deformation

The concept behind the design illustrated in figure 1 was to use the very stiff composite beam (large moment of inertia) to overcome the bimetal deformation along the long axis of the ladder structure resulting from temperature changes encountered between power on and power off. We are designing for a 20° C swing in temperature. It turns out, however, that there are potential problems even over the short axis, the width of the ladder, since it is overhung in this dimension and does not get additional support from the support beam. A [COSMOSWorks analysis](#) of a small section of the ladder structure using (see Fig. 2) shows a thermal deformation of over 500 μm . In this analysis the adhesive is not included but the layers are treated as directly bonded.

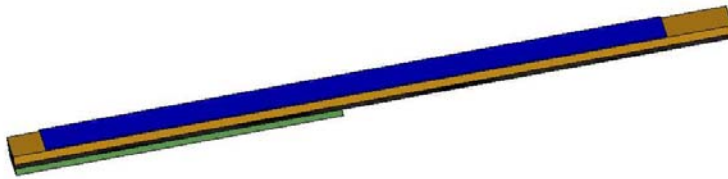


Fig. 2a Short section of the ladder structure. The blue layer is silicon, the tan layer the aluminum/kapton cable, the dark grey layer the base support of the ladder and the green layer the underlying support beam. The adhesive has not been included in this FEA analysis and the layers are modeled with direct bonding. The long dimension in the figure is the width of the ladder which is 22 mm.

Model name: A ladder
 Study name: thermal deformation 2
 Plot type: Static displacement Displacement2
 Deformation scale: 2.70415

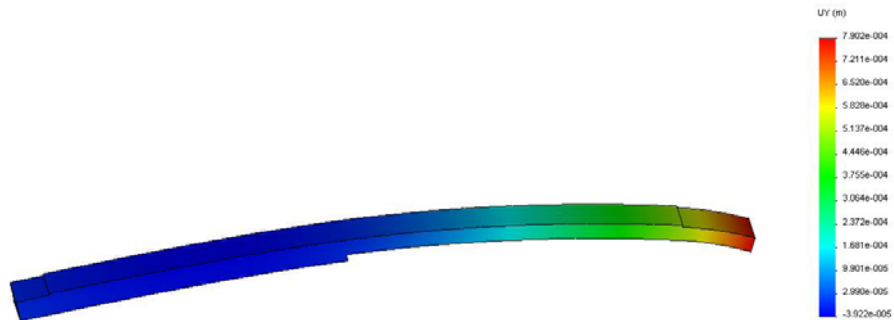


Fig 2b Magnified view of the deformation resulting from a 20° C temperature rise. The outer edge of the detector drops by 500 μm .

This deformation is a factor of 25 beyond the requirement. It is caused by the large CTE of the kapton/aluminum which is 20 times the value for carbon composite and 10 times the value for silicon. One way to alleviate this problem is to mechanically decouple the layers that have different CTEs.

Soft adhesive decoupling

In this study we investigate the use of a soft acrylic adhesive to decouple the layers. This allows differential expansion, but avoids the dramatic bimetal deformation. In early prototypes we have used an acrylic adhesive, 3M 200MP. This adhesive has a Young's modulus of $E = 6.5 \text{ psi}$ and a shear modulus $G = 2.2 \text{ psi}$. The short ladder section of Fig. 2 was modified as shown in Fig. 3 with the addition of two soft acrylic adhesive layers on either side of the kapton/aluminum cable and [analyzed again](#) with a 20° C temperature change.

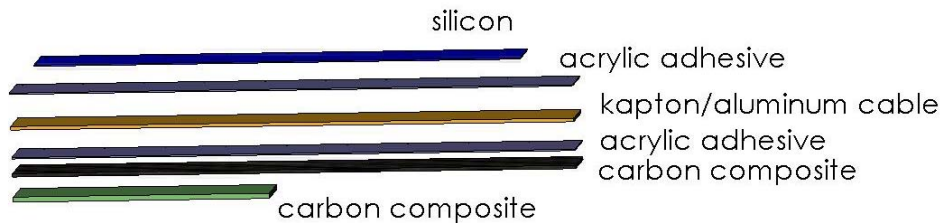


Fig. 3a Short section of ladder soft acrylic adhesive.

Model name: B ladder
 Study name: solid 2
 Plot type: Static displacement Displacement1
 Deformation scale: 408.519

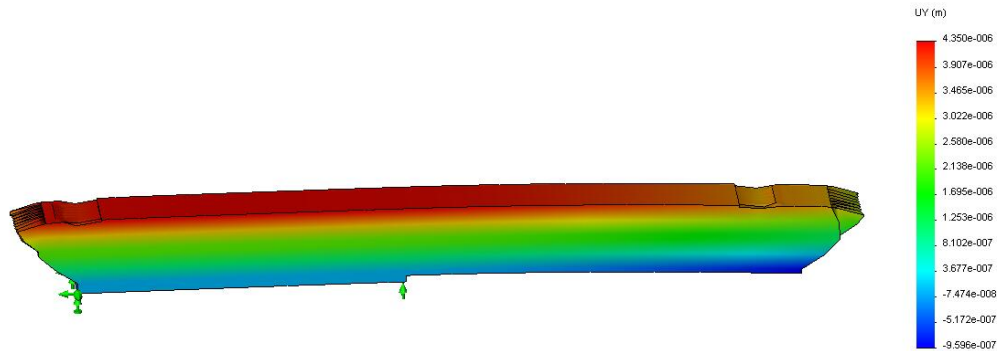


Fig. 3b Magnified thermally induced displacement from a COSMOSworks FEA analysis of detector ladder section shown in Fig. 3a. This shows the result of a 20° C temperature increase. The change in this case is only 4.3 μm and it is due primarily to the large CTE of the adhesive. The soft adhesive decouples the layers so that one does not get the standard bimetal amplified deflection.

As shown in Fig. 3b there is little bimetal bowing and mechanical amplification. The main displacement is a uniform 4.3 μm elevation rise of the silicon. This vertical displacement is driven primarily by the very large CTE of the acrylic adhesive.

Other ways of decoupling can be used such as isolated adhesive pads, but from the standpoint of thermal conductivity it is desirable to have a continuous adhesive contact. Continuous contact helps conduct the heat of the silicon chips to the backside which adds another surface to aid in air cooling.

Thermal deformation of the ladder plus support beam

Performing an adequate FEA analysis of our ladder support beam structure is complicated by the large scale changes from multi thin films to the much larger support beam. The prior requirement of using a very soft adhesive, however, simplifies this complication as it permits effectively a factorization of the problem into two parts with different scales. We first model the thin multi layer ladder by itself with the bottom side constrained to a fixed plane. The FEA analysis gives the shear load on the plane. This shear load can then be used as input to the analysis of the support beam. We can get away with this since the soft adhesive is very compliant compared to the carbon composite support beam. This guarantees that modeling a fixed shear load on the composite beam is a correct representation of the system. The very rigid carbon beam stretches very little so the shear load from the rubbery adhesive remains essentially unchanged.

Rather than model the full length of the ladder we limited the length and demonstrated that the shear stress simply scales linearly as the distance along the long axis of the ladder. A 10 cm section of ladder, see Fig. 4, with the full width, 2.2 cm was [analyzed](#).

The resulting shear stress on the fixed plane for a 20° C temperature rise is shown in Fig. 5.

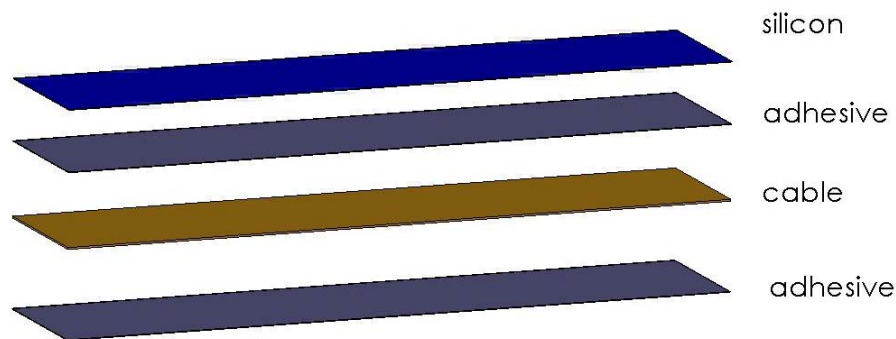


Fig. 4 A section of the ladder used in a FEA to find the shear load imposed on the sector support beam that resulting from a 20° C temperature rise.

The shear load is 0 in the center and scales linearly from the center at 0. 21 psi/in. This shear load is applied to the 4 surfaces of the sector beam where the ladders contact. In this simplified picture the shear load is scaled by the contact surface to give the total ladder load and the load is applied over the full length even though the ladder is not actually this long. There is an additional normal force required to hold the ladder flat to resist the bimetal curling of the ladder alone, but this normal stress (shown in Fig. 6) is small. The integrated force at the end is 3.7×10^{-4} lbf. It was verified with a FEA analysis that this load is insignificant. Applying this load to the end of the sector beam gives a deflection of only 0. 4 μm , so the normal force has been ignored in subsequent analysis.

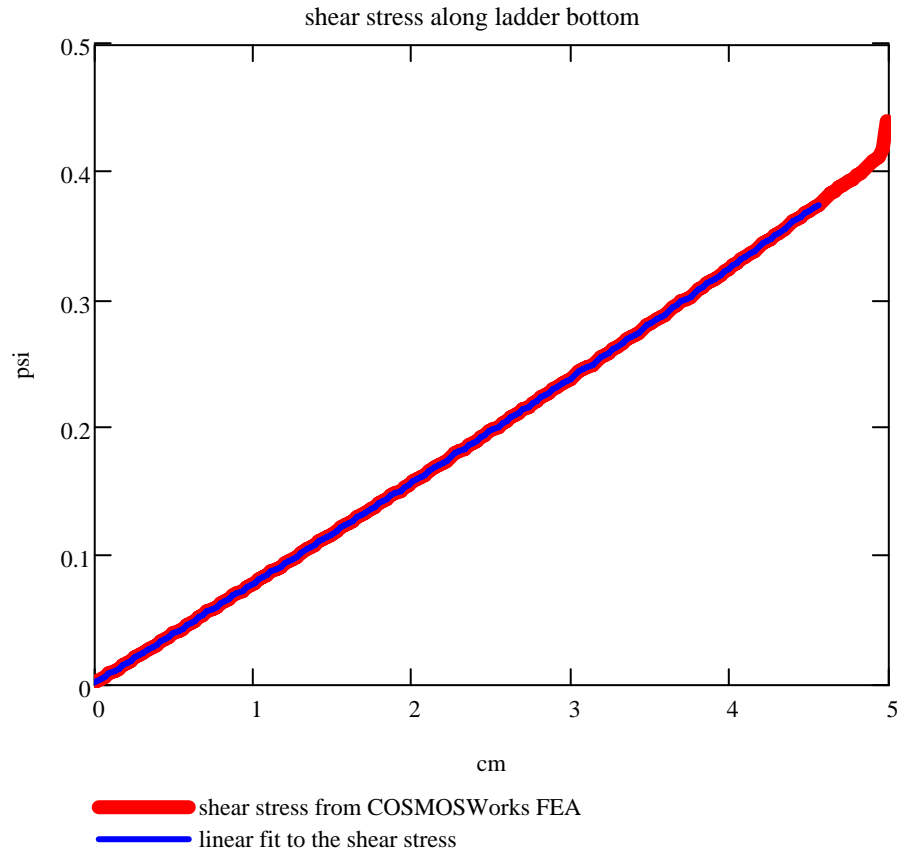


Fig. 5 The shear stress (shown in red) obtained from a COSMOSWorks FEA analysis of a layered ladder structure where the bottom layer is a soft adhesive constrained to a fixed plane. The plot shows the shear stress as a function of the distance from the center along the long axis of the ladder. As expected the shear changes sign as it passes through $z=0$ to negative z values. $z=0$ is the center of the ladder. The blue line is a linear straight line fit to the FEA analysis curve. The up turn at the end becomes more pronounced as the shear modulus of the adhesive is increased.

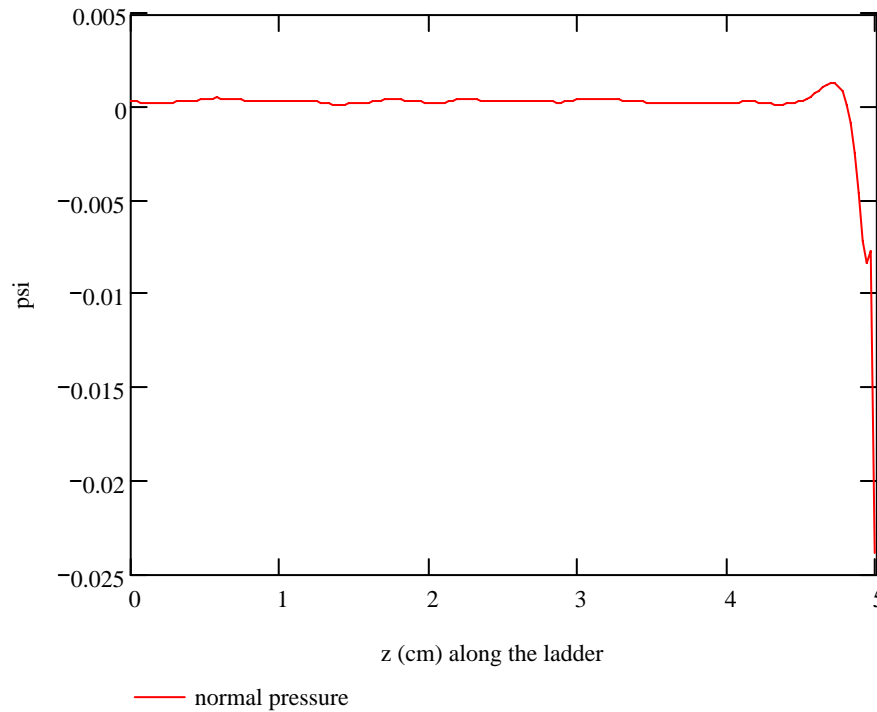


Fig. 6 Normal pressure required to hold the ladder flat as a function of distance along the ladder. This is the pressure required to resist the bimetal curling force of the ladder resulting from a 20° C temperature rise. Integrating from 4.4 cm to 5 cm where the pressure deviates from 0 gives a force of 3.7×10^{-4} lbf. This deflects the sector beam 0.4 μm , so the normal component has been ignored in the rest of the analysis. $z = 0$ is the center of the ladder section which in this case is a total of 10 cm long.

We apply the linear dependent shear stress shown in Fig. 5 to the sector support to [determine with FEA](#) the deformation to expect for a 20° C temperature rise. The stress load has been applied to all 4 ladder positions. The result is shown in Fig. 7. The maximum deformation is at the free end in the middle ladder position and has a value of 31 μm . This deformation is outside of our requirements, but a simple modification to strengthen the end reduces the problem. The result of an [analysis for the reinforced end](#) is shown in Fig. 8. The thermally induced displacement in this case is 9 μm .

Model name: beam
Study name: 2D values 4 surfaces
Plot type: Static displacement (Displacement)
Deformation scale: 972.90

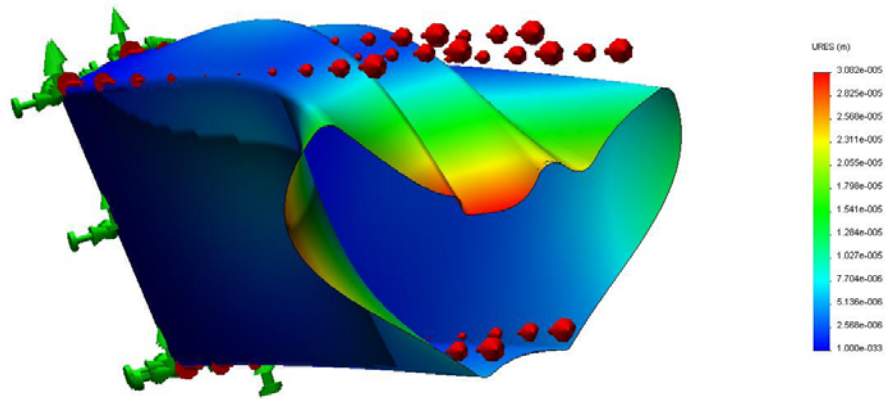


Fig. 7 Thermally induced displacement of the sector support beam for a 20° C temperature rise. The FEA analysis was done by applying a linearly dependent shear force along the length of the beam at each of the 4 ladder positions. The maximum displacement in this case is 31 μm .

Model name: beam
Study name: 4 load snout end
Plot type: Static displacement (Displacement)
Deformation scale: 973

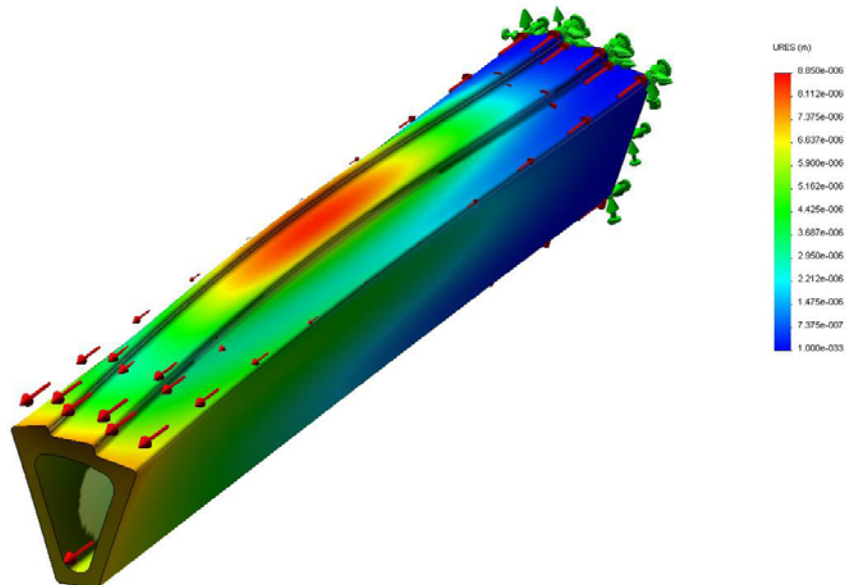


Fig. 8 Thermally induced displacement of a sector beam analyzed as in Fig. 7, but in this case with end reinforcement. The maximum resulting displacement is 9 μm . The beam and end reinforcement is composed of 200 μm carbon composite.

Conclusion of the ALICE style support study

The potentially excessive thermally induced distortions can be reduced by using a low modulus adhesive and a modified design to strengthen the open end of the beam. Through these measures we can reach our design requirement of keeping thermal displacements within a 20 μm window. The adhesive in this case has a very low shear modulus, 2.2 psi. If it is necessary to use an adhesive with a somewhat larger value then this could pose a problem. In these studies the carbon composite was modeled as an isotropic material. This and other simplifying assumptions invite more complete and detailed analysis.

Skin-Foam-Skin Ladder Support

A laminated structure with two carbon fiber sheets separated by RVC foam (Figure 9) was analyzed for thermal distortion.

The structure is composed of 7 layers:

1. Silicon, 50 microns
2. acrylic 3M 467 MP, 50.8 microns
3. aluminum kapton flex cable, 137 microns
4. acrylic 3M 467 MP, 50.8 microns
5. carbon composite cap, 130 microns
6. 3 % RVC carbon foam, 5 mm
7. carbon composite cap, 130 microns

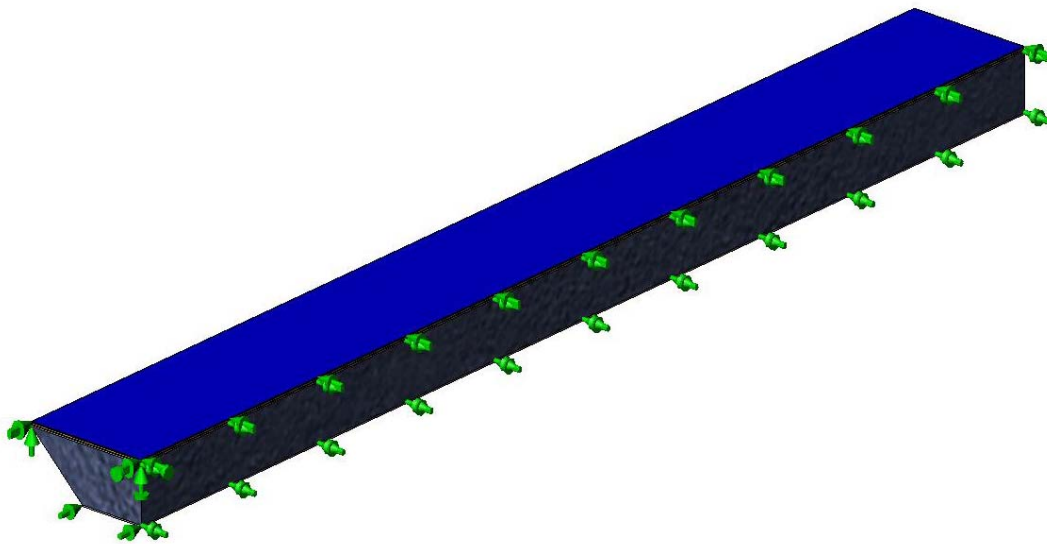


Fig. 9 Quarter section of a ladder with carbon skin – RVC foam core – carbon skin as analyzed. The length shown is 10 cm or a total ladder length of 20 cm.

In this [COSMOSworks analysis](#) the structure was subjected to a uniform temperature increase of 20 degrees C and symmetry constraints were applied on the surfaces

indicated, so the FEA analysis is for a ladder 20 cm long by 2.2 cm. The design includes very low shear modulus adhesive to reduce the bimetal bending effect. This partially decouples the high CTE kapton cable from the rest of the low CTE structure. The FEA results show that the introduction of a decoupling layer causes a deformation different than the classical, [Timoshenko](#), bimetal bending. Classical bimetal thermal deformation results in a circular bend with a radius of curvature that is independent of the sample length. The decoupling layer reduces the shear stress coupling, but the remaining stress accumulates with length so the deformation is no longer quite circular and the radius of curvature is strongly dependent on the sample length. This is illustrated in the FEA results shown in Fig. 10 where the deformation is plotted as a function of z , the distance from ladder center along the long axis. Two cases are plotted, one with a length of 5 cm and another with a length of 10 cm. Included in the figure with the FEA results are z^2 curves matched to the end points. In these cases with very small deformations (large radii of curvature) z^2 curves accurately match circular paths. Again circular paths are what simple bimetal structures conform to. The effective radius of curvature for the two sample lengths (5 cm and 10 cm) differ by a factor of 2.6.

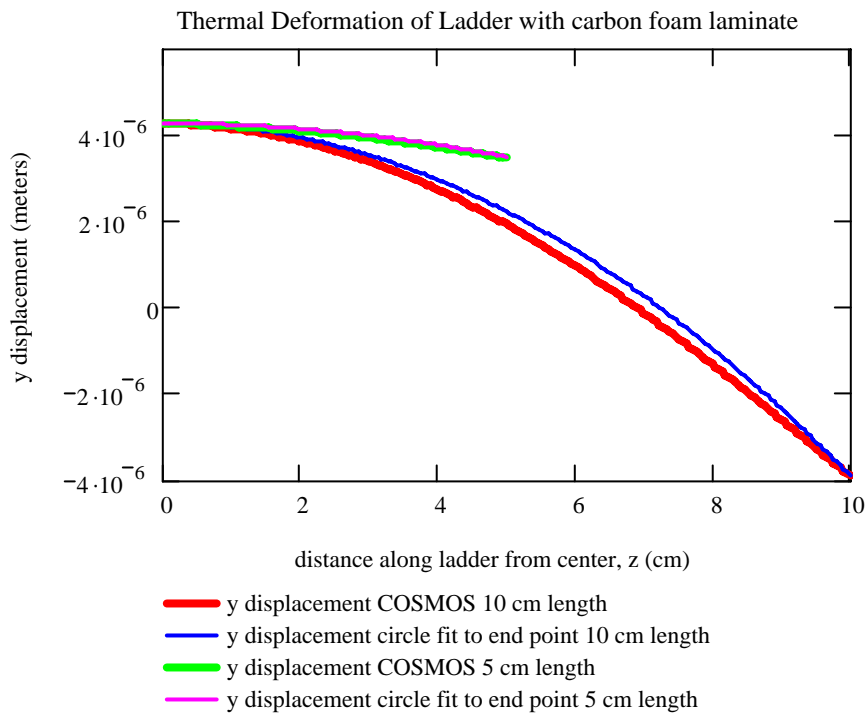


Fig. 10 Thermal deformation predicted by COSMOSworks for a silicon kapton cable ladder supported by a carbon skin – RVC foam – carbon skin laminate which has been decoupled with a low shear modulus adhesive. Results are shown for a 5 cm and 10 cm long section. For comparison circular paths are shown matched to the end points.

The sensitivity to the shear modulus was checked by repeating the 10 cm COSMOSworks run with the shear modulus doubled from 2.2 psi to 4.4 psi and the

elastic modulus was doubled from 6.5 psi to 13 psi. The resulting deformation increased by a factor of 1.5. The sensitivity to the modulus is less than linear, none the less this is an issue to be watched. These modulus values are quite low and would likely be larger if another adhesive is used. Changes in the modulus when operating at a reduced temperature could also be a concern.

A reality check of COSMOSworks was done by analyzing a standard bimetal structure without the decoupling adhesive and the resulting deformation was circular and independent of sample length as expected. The radius of curvature was close to the value obtained from the [Timoshenko bimetal thermostat formula](#).

A magnified deformed picture from the COSMOS analysis, 10 cm length laminate with soft decoupling adhesive, is shown in Fig. 11. Note the lateral expansion of the kapton cable and the adhesive projecting from the unconstrained edges at the end and side. There is also a uniform vertical (y) expansion component of ~ 4 microns. This is driven largely by the large CTE of the adhesive which is unconstrained in the vertical direction.

Model name: L_Lam Lam
Study name: Leo Lam 10 cm
Plot type: Static displacement Displacement2
Deformation scale: 511.407

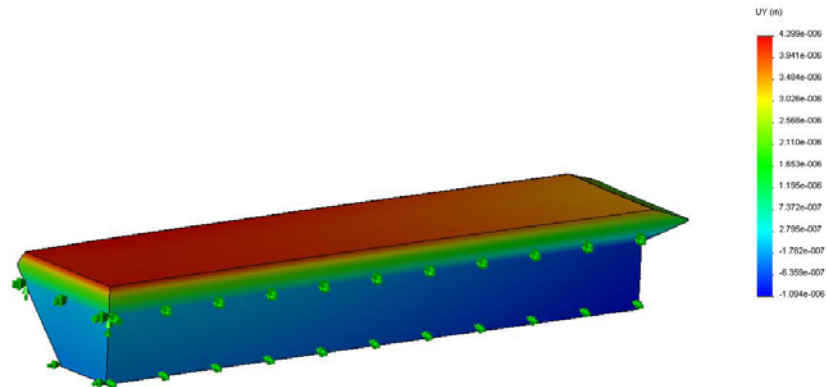


Fig. 11 COSMOS picture of the thermal deformation with a 510 magnification. The color code shows the vertical (y) deformation.

Conclusion of the simple laminate support study

The conclusion of the analysis for this ladder structure is that if supported on one end the ladder will dip by 27 microns. This number is obtained from the slope at the end of the deformation curve shown in Fig. 10.

Increasing the elastic and shear modulus of the decoupling adhesive increases the deformation by a factor of 1.5.

The thermal deformation could probably be significantly reduced with a light weight structure tying the free ends of the ladder together, but this is not analyzed here.

Gull Wing Ladder Support

A gull wing design, see Figure 12, was analyzed for thermal distortion. The structure is composed of 6 layers:

1. silicon, 50 microns
2. acrylic adhesive, 50.8 microns
3. aluminum kapton flex cable, 137 microns
4. acrylic adhesive, 50.8 microns
5. carbon composite cap, 130 microns
6. carbon composite gull wing, 160 microns

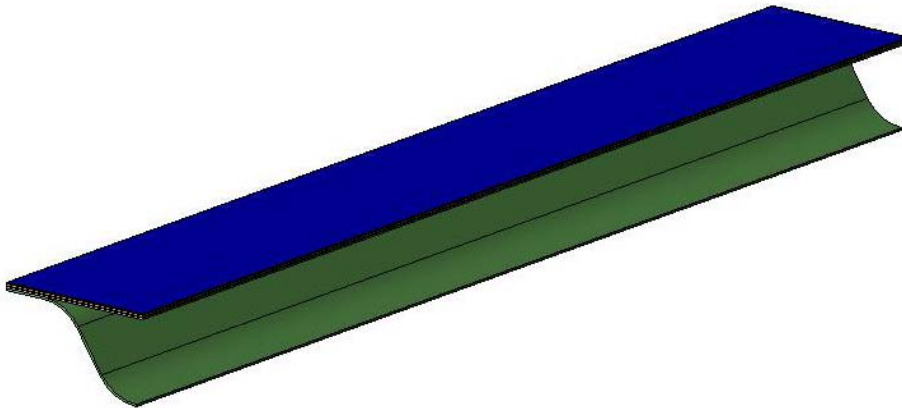


Fig. 12 Silicon pixel ladder with gull wing support beam. The structure as shown is divided in half in length and in width along the two symmetry planes as was used for the FEA analysis. The total size before dividing is 20 cm long by 2.2 cm wide.

In [this analysis](#) the structure was subjected to a uniform 20 degree C temperature change. Like the other structures a low shear modulus adhesive is used to decouple the large CTE kapton cable from the rest of the structure. The resulting deformation, shown in Fig. 13, is like that observed in the previous case with the simple laminate support. Again the deformed shape is not quite circular and the deformation depends strongly on the length of ladder due to accumulated stress with length.

Conclusion of the gull wing support study

The ladder if secured at one end will have a deformation of the free end of 25 microns when subjected to a 20 degree C temperature rise.

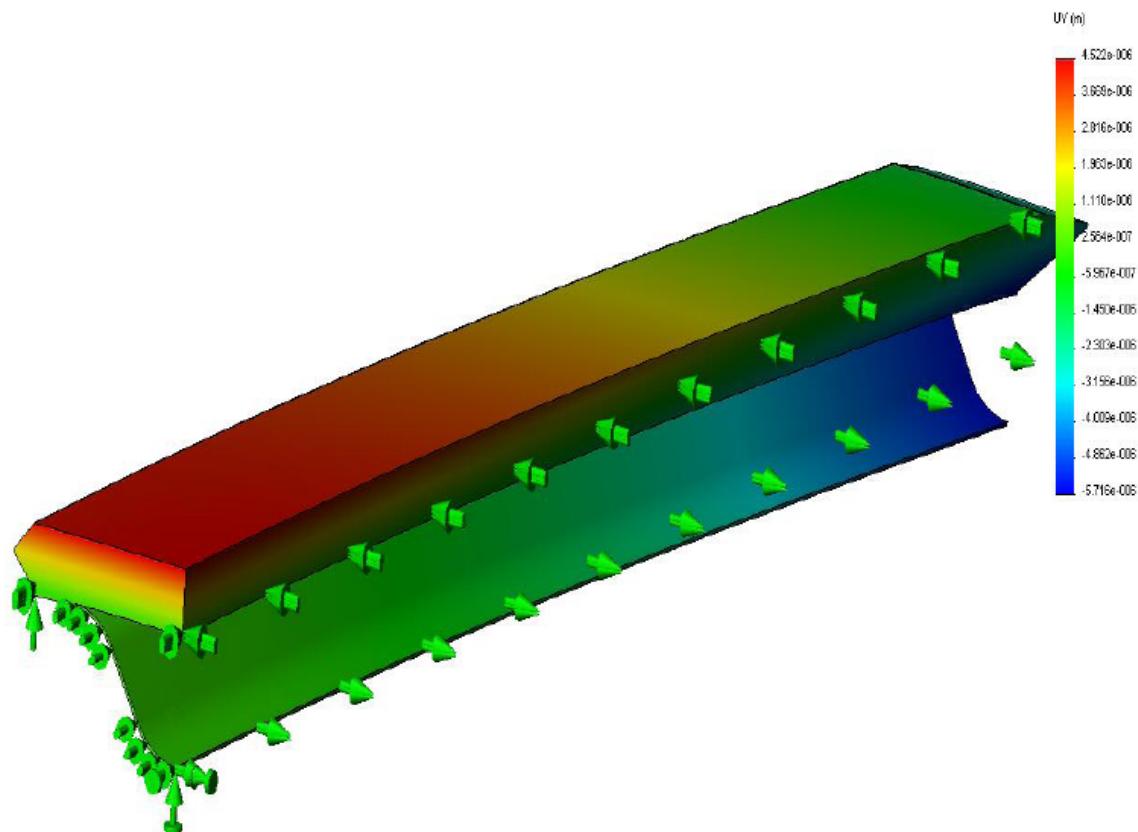


Fig. 13 FEA result for gull wing ladder design subjected to 20 degrees C temperature change. All deformations are magnified by 640. The color scale represents changes in y, the vertical direction.

Conclusion

All three cases, the ALICE style structure, the carbon skin – RVC foam core – carbon skin laminate and the gull wing support give very similar results, 31, 27 and 25 microns deformation with a uniform temperature change of 20 degrees C. The small modification of the ALICE style structure reduces the deformation to 9 microns which is inside of our tolerance envelope of 20 microns. It is expected that reinforcements tying the free ends of multiple ladders together would likewise bring the other two designs into compliance.

A very low shear modulus (several orders of magnitude lower than standard epoxies) adhesive was used in all three structures to decouple the high CTE kapton cable from the rest of the structure. Without this feature the thermal deformations are much larger. Increasing the shear modulus by a factor of 2 increased the deformation by a factor of 1.5. The addition of the decoupling layer leads to a slightly non circular deformation for the later two cases and gives a deformation that goes faster than length squared. It would be of interest to find or derive a simple formula to calculate deformations for the latter two structures which incorporates the soft decoupling layer.

Work materials

All files related to this work including models, calculations and results are located in:

**C:\Documents and Settings\Howard Wieman\My Documents\aps
project\mechanical\ladder thermal thin 3**

The log book, **Pixel designs History Log.doc** , and the original of this document, **Thermal deformation study.doc** , are also located in this directory.